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PRACTICAL RULES FOR THE USE OF THE MAGNETOMETER IN GEOPHYSICAL PROSPECTING

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W. AYVAZOGLOU

(TRANSLATED FROM THE ORIGINAL FRENCH OF
M. C. ALEXANIAN)

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PRACTICAL RULES FOR THE USE OF THE MAGNETOMETER IN GEOPHYSICAL PROSPECTING[1,2]

Translated by W. Ayvazoglou[3] from the
original French of M. C. Alexanian[4]

INTRODUCTION

A large number of organizations interested in the search for mineral deposits have adopted the magnetic method of geophysical prospecting, as it has proved to be the most simple, convenient, and rapid, and at the same time the least expensive in comparison with other methods.

According to the last statistical data, about two millions square kilometers were explored in the United States by different geophysical methods. Ninety-six per cent of this area was prospected for oil and 4 per cent for minerals. Detailed exploration by means of the magnetometer has been carried out over about 85 per cent of this surface.

The great advantages offered by this method resulted in the fact that the magnetometer was tried out in most places in which geophysical methods were applied. The main purpose of such exploration is to obtain the maximum knowledge valuable to the geologist; therefore good geological interpretation of the results of measurements is important. The possibility of drawing practical conclusions from a map representing the results of the study of the terrane depends greatly on the accuracy with which the measurements are made.

The purpose of this article is to show the different sources of error by which the work of an operator may be affected and to discuss the means by which the carrying out of a magnetic survey may be improved.

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[1] From Annales de l'office national des combustibles liquids, No. 4, Paris, 1930, pp. 677-702.

[2] The Bureau of Mines will welcome reprinting of this article, provided the following footnote acknowledgment is used: "Reprinted from U. S. Bureau of Mines Information Circular 6527."

[3] Translator, U. S. Bureau of Mines.

[4] Engineer geophysicist.

All the details and characteristic properties of a magnetometer must be studied thoroughly in advance. A simple knowledge of how to turn the crank of the instrument or to take readings from the scale is not sufficient. Several months of practice in the field are required until all the operations, which seem so simple, are understood thoroughly.

W. M. Barret describes a very characteristic case which is given below, owing to its special interest:

> Large expenditures were made by a petroleum company for the determination of a geological structure by means of a magnetometer. Several organizations were in charge of this work. In 1928 the author had an opportunity to examine the three magnetic maps showing the variation of the vertical component in the same region. The maps looked to be drawn very carefully. The comparison of the maps was easy, as all the measurement were made along the same profiles, drawn according to a regular distribution of the stations of measurement. However, a striking difference could be noted at the first glance. The difference became still greater after the results of measurements were reduced to the same base and the regional corrections were applied. Important magnetic anomalies indicated in one of the maps were entirely missing in the two others. The minimum shown in the last two maps was in the same region, represented as a distinct maximum in the first map. It was evident that this maximum was created solely by the operator. It was then discovered that the operator had worked on magnetic methods only for three months.

Similar cases could be established even with persons having greater experience in operating physical instruments. Many errors assigned to the magnetometers were in reality caused by the lack of ability of the operators, even of the most conscientious ones. To eliminate this disadvantage for others, the author describes in the subsequent paper the practice developed by him in his field work.

The principles of construction of magnetometers used in geophysical prospecting, known under the name of magnetic balances, are the same. The magnetometer used the most is that manufactured by Askania (for vertical as well as horizontal components) and next are the magnetometers constructed by Töpfer, Exploration, and Örtling. All these instruments are well elaborated and almost of the same order of sensitiveness.

Thus the quality of the work done by the operator depends exclusively on his ability to use the instrument. The operator must know thoroughly how the different constants, specified by the constructor in the bulletin of delivery, should be verified. These constants change usually during transporation on account of the shocks suffered by the instrument; sometimes (very rarely) the determination of the constants is not made with sufficient accuracy before starting on the expedition. Besides, the instrument is in general not adjusted according to the region in which it is to be used. Therefore the operator-geophysicist must know how to make all these adjustments.

SOURCES OF ERROR

The sources of error may be due to (1) construction, (2) observation, and (3) natural causes.

I. ERRORS DUE TO CONSTRUCTION

1. Variation of the Magnetic Moments of the System of Magnets and of the Bar Magnets

Even during a long period of use the variation remains insignificant under the condition that the magnetometer box is not opened too often. The magnets (lamellae) are manufactured from very good tungsten steel or chrome steel. The bar magnets, which serve as auxiliary compensation magnets, are from the same material. A box magnet with the magnetic moment equal to 961, as determined by the Askania Works in Berlin, was sent after one year to the same manufacturers for reexamination; the new value was established as being equal to 957; this proved that the variation was negligible.

This determination can also be carried out in the field, thus making the sending of the apparatus or the accessories to the manufacturers for the adjustment unnecessary. It is only necessary to have a standard bar magnet and keep it, well wrapped in cotton, in the laboratory away from ferromagnetic objects; the magnetic moments of the magnets used in the field can be determined by comparing them with the standard bar magnet (see the instructions issued on this subject by the manufacturers and laboratories that design such instruments). To keep these magnets in condition, the smallest shocks, humidity, and sudden changes of temperature should be avoided; the magnets must, besides, be kept away from ferromagnetic objects.

During the first six months the magnetic moment of these bars decreases appreciably, but after this time it remains almost without change; thus, the moment must often be verified during the first six months after the delivery of the bars.

The magnetic system in Haalck's variometer consists of two pairs of magnetized lamellae in the form of a cross; the ratio M_1/M_2 of the magnetic moments of these two pairs of lamellae must be determined at least every three months, as M_1 and M_2 never change in the same proportion; thus the value of the ratio changes in the course of time, although the lamellae are almost identical. The ratio M_1/M_2 varies usually from 0.85 to 0.95.

2. Displacement of the Center of Gravity of the Magnetic System

Displacement of the gravity center of the magnetic system usually results from shocks and temperature changes. The center of gravity is brought to its initial position by operating the two lateral screws secured to the cubical body of the magnetic system.

If the instrument is well adjusted for a fixed region the small displacements of the zero point, which may be established during the measurements, can be regulated by means of compensator magnets P; in this case the image of the scale must remain within the field without the interposition of these magnets; in other words, the lateral screws must be operated until the magnetic system of the instrument is almost horizontal or vertical (case of the balances assigned for the measurement of the vertical or horizontal component). The purpose of displacing of these screws is to displace the center of gravity along the abscissa.

A third screw, larger than the two mentioned above, secured beneath the cubical body, serves for adjusting the sensitiveness of the apparatus; by the operation of this screw the center of gravity of the magnetic system is displaced along the ordinate; the closer the center of gravity is to the axis of oscillation the more sensitive is the instrument. However, care must be taken that they do not coincide, as this may result in an unstable state of equilibrium of the system of oscillation. A useful compromise should be established between these two factors; the operator should not endeavor to secure a sensitiveness which can not be maintained by present-time instruments.

Being adjusted for a certain region the different constants of the apparatus must be determined at the place, as their values are necessary for the final calculations of the stations of measurement.

3. Displacement of the Zero Point of the Scale

The displacement of the zero point may result from shocks and the displacement of the magnets P. If the error caused by the displacement is greater than the experimental errors (± 10 gammas to ± 12 gammas), all the stations along the same magnetic profile at which measurements were made previously to the establishment of the error must be started over again.

This displacement is usually discovered after the return to the base station. The role of the latter is primordial, as not only all the following stations are connected with it but because it serves also for the discovery of the displacement of the zero point.

After having completed all corrections for the temperature and the diurnal variations, and in order to find out whether the readings taken in the beginning of the day work are the same, it is necessary to return to the base station three times during a working day -- in the beginning of the operations, in the middle, and at the end of them.

Therefore the place of the base station must be chosen so that it may be easily reached during the operations.

If the difference between two readings taken at the base station is great, this difference must be distributed either linearly among all the stations affected, or, if the operator wants to make sure that the results of measurements are accurate, the measurements must be made all over again. The application of the linear distribution of the error may be recommended for trained operators.

4. Determination of constants

Scale constants

a. Vertical Component.- In determining constants the following two methods may be used:

(1) the direct current frame method, and
(2) the method by using the magnets P (Gauss' principle).

1. By using the first method the coefficient of the self induction of the coil of balances manufactured by Askania, Töpfer etc., must be known. This is furnished by the manufacturers. Haalck's universal variometer does not require the use of the frame as, according to the theory of the apparatus, more simple, although less accurate, methods may be applied. The advantage of the use of the frame consists in obtaining great accuracy in the measurement of the scale constant; on the other hand, its transportation in the field is not sufficiently convenient.

2. This is why the method of using the magnets P must be preferred. In this case the operations are simple and easy; of course, the magnetic moment of the magnet used and its distance in millimeters from the axis of oscillation of the magnetic system of the instrument must be known.

By combining these two methods, the ratio M_1/M_2 of the magnetic moments of the two pairs of magnetized lamellae of Haalck's variometer can be determined with a sufficient accuracy; the operation to be carried out for this consists simply of eliminating the constants.

b. Horizontal Component.-

1. The case of simple balances (Askania, Töpfer, Örtling).- The operations are similar to those mentioned above, with the sole difference that the magnetic system oscillates in the north-south magnetic plane instead of the east-west. But the determination is more delicate. All the possible care must be taken for preserving the horizontal position of the instrument (the vertical position of the principal axis must be as perfect as possible). An inclination corresponding to one-half division in the level may cause an error in reading the scale equal to ± 10 gammas. In the case of the vertical component a difference in the level equal to almost one or even one and one-half divisions can be tolerated in the course of the measurements; the vertical position of the instrument measuring the horizontal component must be almost perfect.

2. Case of Haalck's variometer (Exploration).- The operations require much time and can be carried out only by using the auxiliary compensation magnets P and K. In addition to the horizontality of the instrument, care must be taken in turning its different parts exactly at 180° about the axes. Because the operations take time and are delicate it is hard to know in what sense the errors caused by them may accumulate. In this case the possible errors may arise from:

(a) The inaccurate determination of the magnetic north-south (in connection with the magnetic east-west); this is the greatest and the most important error which may be made as it will probably affect the observations in most cases.

(b) The readings taken from the dial by means of the vernier. The taking of the readings should be well practiced, as this is not as easy as is usually expected. Even the most trained persons can make errors. The readings must be verified at least twice.

(c) The involuntary shocks produced by turning the support of the magnets K about its axis.

5. Temperature Constants

The determination of the temperature constant is the most delicate operation and requires long time. Let us suppose that the temperature coefficient of a magnetometer is to be determined. The sole mean for examination is to have two identical models, the temperature coefficient of one of which is exactly known and which serves simply for the determination of the diurnal variation. Under these conditions the latter can be very well replaced by a corresponding magnetograph (recording apparatus). The method adopted at the "École Nationale Supérieure du Pétrole" is the following: The magnetometer under examination is put in a small, well-isolated room (to avoid the draught caused by heating); the temperature is gradually increased from the center (with a constant thermal gradient). The corresponding readings are made from the scale, taking care that a uniform temperature inside of the instrument is maintained. For this purpose an endeavor is made to obtain an accord of about one-tenth of 1° between the readings of the two thermometers, the one in the room and the other in the apparatus; a magnifying glass may be used for reading if necessary. During several days (about ten) readings are made twice a day, in the morning and in the evening. As the corresponding diurnal variations are known exactly, the mean value and, as accurately as possible (at about 1/10), also the temperature coefficient can be deduced.

To make the error as small as possible it is necessary to use always the method of the least squares. The value obtained in this way is usually very correct. But there arises the following question. What may happen if the constant thermic gradient is no longer maintained? During our own investigations we established that the temperature coefficient μ does not have a constant value but is to a certain degree a function of the thermic gradient; of course, this difference does not, in general, much affect the precision of the final results.

In case of Haalck's magnetometer (No. 36, constructed by Exploration) the measurements were carried out, according to the method indicated above, at a mean temperature of 22° C; for the vertical component the variation of μ was between 7.74 (for a variation of 0.2° C. per minute) and 7.96 (for a variation of 1° C. per minute). For practical use we adopted $\mu = 8.0$; owing to the fact that the readings of the thermometer could be easily made by the naked eye with an accuracy equal to about ± 2/10 of a division, the absolute error did not exceed 3 gammas; this error can be considered acceptable.

Thus we are of the opinion that, in order to reduce the probable errors, instruments with the smallest possible temperature coefficients should be acquired. These values in balances manufactured by Askania are in general from three to five.

The method of heating can be accomplished satisfactorily by using an electrical radiator regulated by inserting a rheostat in the circuit.

Some authors prefer to put the magnetometer into a box, the temperature of which is gradually increased by electrical heating. This method seems to be very satisfactory; some others work simply in the open air, but this practice must be rejected, as there is never a uniform thermal stability between the instrument, the coefficient of temperature of which is to be established, and the ambient air. Even under the best conditions there will always be a difference between the temperature indicated by the thermometers of the instrument and the real temperature.

During the beginning and the end of different operations made in the field at one station the temperature varies often from 3 to 4° C., especially if the work is done under full sunshine at about 11 a.m.; as the variations of the thermal conditions of the magnetic system and the indications of the thermometers are not simultaneous, there is necessarily a difference between them.

The temperature shown by the thermometer at a certain moment of operations may thus not correspond to the exact correction to be applied to the results. The thermometer indicates the same temperature as the magnetic system at a moment when the temperature of the latter is higher (the temperature supposed to be increasing). Thus it is desirable to know this difference and in particular the inertia of the thermometers of the instrument. Accordingly, always taking the mean value of the initial and final temperatures; and often even to take into account, in case the thermic gradient is very high, a third reading made between the observations.

6. Variation of the Horizontality of the Apparatus

In the first place it must be verified whether the level of the instrument is horizontal with respect to its support; if not, it must be regulated according to the rules applied to topographic instruments. Besides, at every station it must be examined whether the level has been deranged or not by involuntary shocks caused during transportation. As a rule the horizontality of the instrument must always be regulated carefully and it must be observed during the whole time of operations that the bubble is not displaced at more than one-half division. On the other hand, if the soil is wet and soft, the tripod may be deranged without being noticed, and it results that the large readings made from the scale may be attributed involuntarily to the local anomalies, although in reality they are due only to these displacements of the tripod. The same phenomenon may occur in case of a frozen ground.

In putting the instrument at a station it is necessary to drive the tripod legs well into the ground and to regulate the table so as to make it almost horizontal before the apparatus is placed on it. By this the operating of the three levelling screws up to the end of their windings is avoided.

7. Condition of the Knife Edge

The knife edge is the most delicate part of the instrument, as the whole sensitiveness depends on it. Greatest care must be taken by the operator to keep it in good condition. Therefore it must never be forgotten to clamp the magnetic system after the completion of operations at a station. The knife is of agate or quartz, which are very fragile; all shocks of the edge against the pivots, which are of the same material, should be avoided. All these accessories are perfectly elaborated; the edge may be of cylindrical, circular, or parabolic form.

From this fact it is clear a priori that the constant of the scale can not have the same value at the different parts of the scale, because the distance of the center of gravity of the magnetic system to its axis of oscillation varies when inclined.

In order to find the relation by which the coefficient of the scale is connected with the inclination of the magnetic system of the variometer, the method applied in the laboratories of the Ecole Nationale Supérieure du Pétrole et des Combustibles Liquides is the following:

The magnetic system is given increasing inclinations by intermediation of a bar magnet P placed under the instrument over a graduated ruler (second position of Gauss); after this the relative position of this bar with regard to the center of oscillation of the magnetic system is changed, and at each position of it, which must be well determined, the constant of the scale is determined by the frame method.

After this the curve K = function E is traced, in which K is the constant of the scale and E the inclination expressed in divisions of the scale.

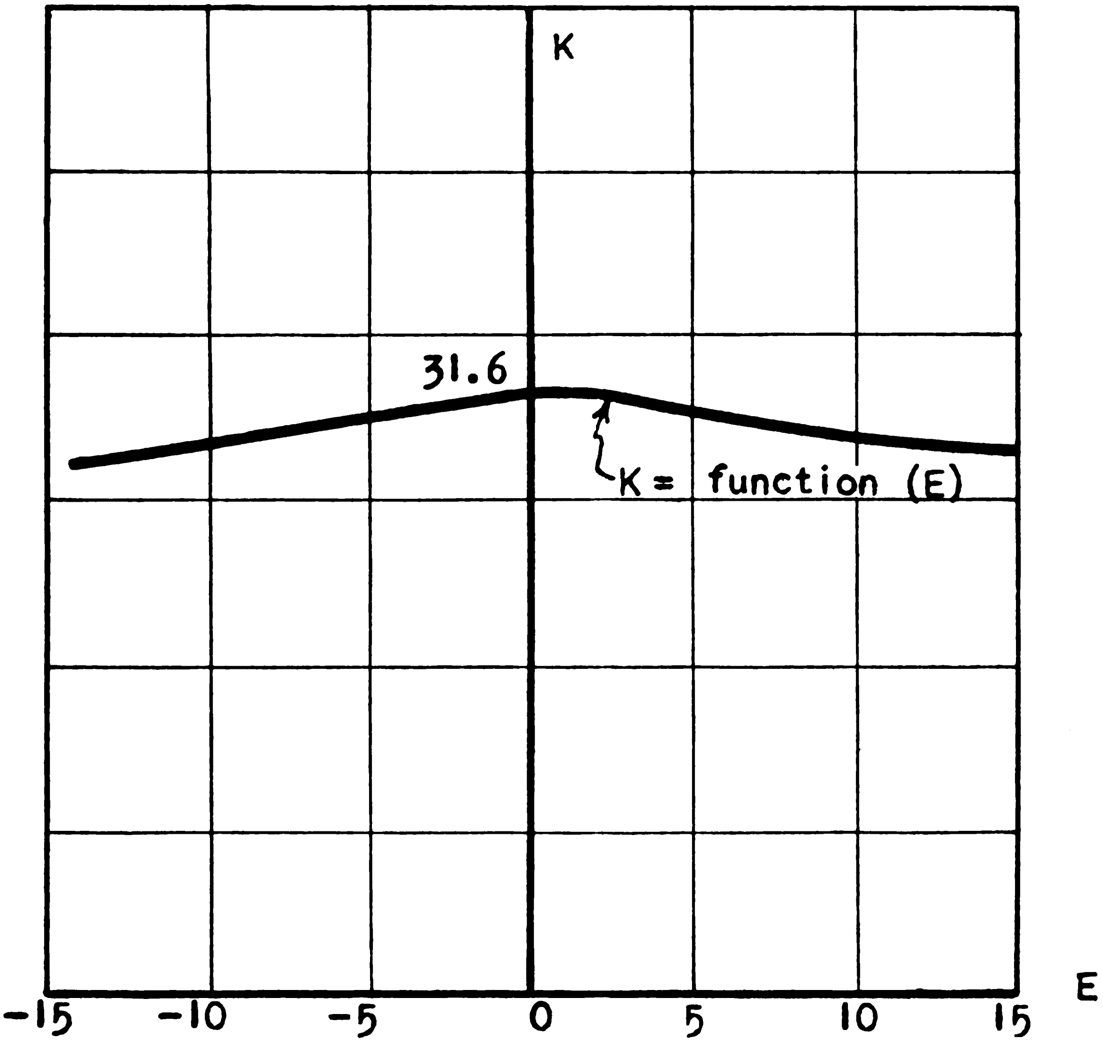

Figure 1.– Variation of scale constant K with inclination E, for Haalck's variometer, method of the École Nationale Supérieure et des Combustibles Liquides

Thus by application of this method to the vertical component of Haalck's variometer we obtained the curve shown in Figure 1.

This curve is slightly dissymmetrical with regard to the axis of ordinates and it shows that K diminishes in case of strong inclinations of the magnetic system. This means that the sensitiveness of the apparatus increases with the increase of inclination. These results are in full accord with those obtained by the United States Coast and Geodetic Survey.

In our case the mean values of K which we deduced from tests are as follows:

E	K	E	K
0	31.6	0	31.6
+ 5	31.4	- 5	31.2
+10	31.0	-10	30.8
+15	30.6	-15	30.4

Contrary to the usual opinion, the knife edge is not spoiled very quickly; we can even declare that it can be used as long as the magnetometer, if the magnetic system is liberated with special care and always in the same manner. Rough turning of the handle must be avoided especially. If a harsh noise is heard from the shock of the knife against the pivot, this is unfavorable. Locking the instrument before being transported must never be forgotten.

II. ERRORS DUE TO OBSERVATION

1. Selection of Stations

In selecting a station for measurements the following should be taken into consideration: (a) its accessibility, (b) the physical conditions of the ground, (c) and the direct action of the sun and wind.

(a) Stationing on a sloping place or on a road, unless the latter remains for the most time unfrequented, must be avoided. In case of the necessity to reach the station across an uneven terrain the apparatus should be carried with great precaution by the operator himself.

(b) Lawns and soft ground should be avoided. Before starting the measurements it is necessary to examine whether the movements of the operator around the tripod affect the horizontal position of the instrument or not. The operator must be sure that the instrument is established firmly.

(c) It must be tried to remain always in the shadow, at the same time avoiding the draughts. A place between two stems of large trees where the draught is sometimes very great should be avoided; in this case the error may be caused not only by the variation of the thermal conditions around the instrument, but also by the mechanical action of the wind by which the instrument can be moved in an irregular way. In selecting the base stations the operator must be careful to see that these stations are located so as to remain in the shadow during the whole day. If the frequent returning during the day to the base station is not convenient, it is preferable to select several base stations and then unite them into one station.

Finally, a station must always be marked by a number or a latter and the date of the operation should not be forgotten.

2. Setting the Instrument

All the objects which can affect the magnets should be left behind when going to the field. It is a bad habit to remove the objects at each station and then to carry them after the completion of the operation to the next station. Special care must be taken that such objects as, for example, wrist watches, keys, iron belt buckles, purses, iron and nickel plated cigarette holders, chains, necktie pins, buttons, and nailed boots are not used. The operator must always make sure that there are no magnetic objects around the instrument.

Telegraphic posts, electrical lines and towers, wires of barbed iron, the proximity of villages and especially of factories must be avoided as much as possible. Stations sites must be selected at least 10 kilometers from large cities.

In placing the instrument upon the table of the tripod the hooks must be closed without using too much force.

3. Position of the Operator

In making the readings the operator must try to occupy always the same position with regard to the magnetometer. It must always be remembered that the apparatus is very delicate and expensive. By doing so the operator will instinctively pay great attention to it during the operations. The fundamental principle that an apparatus should be used by the same operator only, and must never be loaned, should also be adopted. Nobody should be permitted to approach the apparatus; even the assistant must stay away at about 10 meters distance. During the readings the operator should cross the hands behind his back; he must try to make the readings by opening both eyes equally in order to avoid the parallax error and besides in order not to impair the sight. Before starting the work on a series of stations the operator must not forget to adjust the telescope.

The opening of the box of the apparatus in order to explain its function to the visitors must be avoided; each operation of such kind injures the sensitiveness of the instrument.

4. Carrying Out of Measurements

Two persons are sufficient for carrying out measurements with one apparatus: The operator, who takes the readings and transports the apparatus, and his assistant, who writes down the results and makes the necessary numerical calculations; the latter measures also the distances between the respective stations and transports the accessories (boxes, maps) if any. The selection of the stations is made by the operator who chooses the places considered to be the best for the measurements. The assistant must know how to find the correct places of these stations on the map. Some operators prefer to hire assistants from the population of the region in which they are working. This can not be recommended as the quality of the work becomes very poor. In the first place the assistant must know what he has to do, as it is very disagreeable to explain to him every step of his new occupation. Calculations required on the spot during the time the operator adjusts his instrument will besides be certainly above his intellectual faculties. Finally, and this is important, he can not give explanation if during the day the operator or even he himself has made a mistake or has forgotten to carry out some operations. Therefore it is necessary that the assistant also be, to a certain degree, able to give advice to the operator. Finally, after each station, the operator must make certain that the magnetic system of the instrument is well balanced and that the safety device is well inserted.

5. Reading From the Scale

Before taking a reading the scale must be perfectly lighted in order to avoid the formation of the image of the sun on the scale. Besides, if the lighting is very bright the use of the rotating mirror becomes unnecessary.

During the reading the operator must be able to see clearly at least 1/10 of one division of the scale; this corresponds to the measurements equal from 2 to 3 gammas (relative error); some operators are even able to read about 1/20 of a division. This is usual with our pupils who are trained in geophysical prospecting.

After having made a reading the operator must ask the assistant to repeat it accurately. The same brief and precise expressions should be used always; this will make the work methodical and even mechanical.

The readings of the temperature before and after the operation should not be forgotten. The assistant must watch all the operations of the operator. Finally, after the termination of readings at a station the operator must ask himself whether he did not forget something.

6. Determination of the Magnetic East-West. Influence of the Bad Orientation of the Instrument

(a) If Lloyd-Schmidt balance is used it is necessary that in putting the compass on the table of the tripod the determination of the east-west magnetic direction is made with an accuracy equal to at least $\frac{1}{2}^{\circ}$; the graduation of the compass is divided into degrees. After a little training readings with an accuracy equal to $1/3^{\circ}$ can be made.

(b) If Haalck's variometer is used, the determination is much more delicate; readings from the limb can be made with an accuracy equal to 30" of the arc. An orror in orientation equal to 1' of the arc produces easily an error equal to 3 gammas for an instrument the scale constant of which is of the order 30 (for the two components of the terrestrial magnetic field). In general the sensitiveness of Haalck's variometer is higher than that of Lloyd-Schmidt balances; this can be proved by using both instruments in the field, as well as from the theory of their construction.

Finally, by using Haalck's variometer attention must always be paid to a perfect determination of the east-west magnetic direction of the base station because the accuracy of all the further results depends on it.

7. Final Calculations

As a rule, final calculations are made in the evening after the conclusion of the work in the field. We recommend, of course, that preliminary calculations, giving rough results, be made at every station. In this case if a considerable anomaly is established the operator must immediately return to the previous station and find out whether this anomaly is not due to the shift of zero point of the scale between the two stations; if the same value as obtained before is found, the operator can be assured that the measurements are correct.

Final formulas always give variations of the two components of local magnetic field in gammas ($1\gamma = 10^{-5}$ gauss).

These formulas contain:

1. Readings made from the scale.
2. Exact values of the constants of the scale.
3. Diurnal variations.
4. Regional corrections (longitude, latitude).
5. Temperature constants.

Values of magnetic moments of the auxiliary magnets, as well as those of the magnetic system of the instrument and the regional values of the two components of the terrestrial magnetic field, enter indirectly into the expression for the constants of the sacle. Notwithstanding the variety of these different quantities the application of these formulas is easy and entirely mechanical.

III. ERRORS DUE TO NATURAL CAUSES

1. Displacement with Regard to Geographic Coordinates

In moving along a wide region the terrestrial magnetic field is submitted to a continuous variation in longitude and in latitude without the intervention of any disturbing foreign magnetic body. Thus, on the terrestrial globe, the vertical component varies from -0.67 to +0.63 Gauss (counting from the south pole toward the north magnetic pole), while the horizontal component, considering it positive on the whole surface of the earth, varies from zero (at the magnetic poles) to 0.39 Gauss (equator). Under these conditions the corrections to be applied are about, for the vertical component:

In latitude, 8 gammas per kilometer,
In longitude, 1 to 2 gammas per kilometer.

The latter correction can usually be neglected in practice; it may be taken into account if the anomalous curves are directed from east to west.

For the horizontal component:

In latitude, 5 gammas per kilometer,
In longitude the correction is negligible.

It must not be forgotten that if the movement proceeds toward the north the corrections are:

To be subtracted for the vertical component;
To be added for the horizontal component.

If the movement proceeds toward the south, the operations are to be effectuated in the inverse sense.

Thus the magnetometer used is adjusted for a relatively limited region. As a practical rule it can be adopted that this area is extended toward the north and the south from the base station which was used for the adjustment of the constant of the scale of the magnetometer. Beyond these limits it is necessary to make adjustments for the new region. The use of a magnetometer must, approximately, be limited by an arc equal to 220 kilometers of a terrestrial meridian, say 2° of difference in latitude, for example, of the length of the Rhine Valley (Fossé rhénan).

2. Diurnal Variations

It is known that the terrestrial magnetic field displays secular, annual, and diurnal variations. The two first are not important to the prospector, due to their extreme slowness. The effect of the diurnal variation is on the contrary very intense during certain hours of the day; therefore we recommend working in the fieldwithout interruption from 10 a.m. to 3 p.m. This is the time of the day when the diurnal variation of the terrestrial magnetic field is the smallest.

The results of the measurements of the diurnal variation may be corrected in the following ways:

(1) By taking the exact values of this variation from a magnetic observatory--for example, for France and Algiers from the observatory of Vol-Joyeux.

(2) By installation of a temporary observatory in the center of the region to be prospected by mounting there a magnetometer and assigning a special observer. This method is the best because the diurnal variation of the terrestrial magnetic field is not entirely identical in all the parts of the same country. This method requires, of course, additional expense, thus it can be used only by comparatively rich organizations. Its great advantage consists of the fact that the different values of the diurnal variation can be obtained immediately. In this case the work can be carried on from 9 a.m. to 5 p.m.

(3) For organizations which are less fortunate the following manner of work can be recommended:

Mean monthly values for each hour of a day of diurnal variations of the two components of the terrestrial magnetic field of the previous year or of the year the results of which were published by the Institut de Physique du Globe de l'Université de Paris are taken and curves showing these variations are traced at a suitable scale; this will give 12 graphs which can be used during the operations in the field.

Of course values with an approximation of from 3 to 4 gammas only can be obtained, but this error is acceptable. According to experience obtained in the field it can be stated that this method gives very satisfactory results from the viewpoint of industry.

(4) The last procedure is that of making the work a mechanical one by using for the two components recording instruments called magnetographs. The results obtained by these instruments are, of course, not as accurate as desirable. Their sensitiveness is not very great and they are affected, especially by the variation of the temperature. The registration is made in these instruments photographically, but its enlargement is not sufficient, the course of the luminous ray being very short. Besides, they are too heavy for convenient transportation, their handling requiring great care, suitable installation, and trained personnel. Thus, taking into consideration the great expenses and difficulties caused by their transportation it is better not to use them.

As a rule the amplitude of the diurnal variation of the terrestrial magnetic field is twice as great in summer as in winter. With regard to the months the courses of the curves of the diurnal variation are the same for the following series of months:

January, February, November, and December.
March, April, September, and October.
May, June, July, and August.

All the curves show a minimum at noon. There is a perfect concordance of the same series of the months of the year with the variation of the mean temperature. In winter the variation of the temperature is very small, owing to the fact that cloudy days are the best for the work of the prospector (the most uniform temperature); the winter is theoretically favorable for the magnetometer work, but unfortunately during this season the atmosphere conditions make the work often impossible.

3. Magnetic Storms

There are often days (especially during the summer) when the magnetic measurements seem to be entirely incoherent. This is due to the irregular variations of the terrestrial magnetic field, called magnetic storms.

In case of such storms it is absolutely useless to continue the measurements, even if the storm lasts several days. In order to know in advance the date of the storm it is recommended to stay in close relation with a magneti observatory from which the information on the storm may be obtained by wire. If the operator works far away from civilized places the presence of a magneti storm can be established by him from the irregular courses of the profiles. A person sufficiently trained in magnetic survey may easily establish this.

4. Electrical Currents

Networks of direct current are fatal to the magnetic survey, thus they must always be avoided. The effect of the alternating current, with which the surveyor has usually more chance to come into contact, can, on the contrar be almost neglected; in this case the sole inconvenience arises from metallic poles; 150 to 200 meters distance should be kept between the poles and the instrument. Electric traction often produces considerable effect on the measurements.

In order to establish this it is sufficient to put a magnetometer at 100 meters distance from a moving electric vehicle (tramway or railway); the parasitic electromagnetic effect attains a value from 80 to 100 gammas.

IV. CRITICISM OF THE RESULTS OF MEASUREMENT

1. Accuracy of Measurements

(a) The total error which can be allowed to be made by a trained and conscientious operator should not exceed ± 10 gammas. This error can be apportioned as follows:

From 2 to 3 gammas to the reading from the scale;
From 2 to 3 gammas to the reading of the thermometers;
From 3 to 4 gammas to the estimation of the diurnal variation.

(b) In order to estimate the accuracy of the measurements it is recommended to make, as often as possible, the measurements twice at the same station and at different intervals. Thus, let us suppose that in order to determine the values, the variation of the vertical component is measured and

$$\Delta Z_1;\ \Delta Z_2;\ \ldots\ldots\ldots;\ \Delta Z_n.$$
$$\Delta Z'_1;\ \Delta Z'_2;\ \ldots\ldots;\ \Delta Z'_n.$$

are the two series of the measurements made at stations 1, 2 ... n. The differences

$$\begin{array}{c} \Delta Z_1 - \Delta Z'_1 = \varepsilon_1 \\ \underline{\Delta Z_2 - \Delta Z'_2 = \varepsilon_2} \\ \Delta Z_n - \Delta Z'_n = \varepsilon_n \end{array}$$

represent the relative errors made at these stations; the mean quadratic error will be:

$$\varepsilon = \pm\frac{1}{n}.\sqrt{\varepsilon_1^2 + \varepsilon_2^2 + \ldots. + \varepsilon_n^2}.$$

The operator must obtain from his measurements $\varepsilon \leq 10$ gammas. Therefore the consideration of the mean quadratic error is, for a quick estimation of the measurements obtained, very useful.

3. Coordination of Stations of Measurement

Very often the geologist is especially interested in obtaining for his investigations the absolute value of the terrestrial magnetic field. This determination by means of absolute instruments is tedious and difficult, especially if a great area is to be surveyed. In this case the difficulty can be removed by attaching to the absolute instruments a magnetic variometer, The technique of the work will then be as follows:

A limited number of stations of absolute measurements in the region under consideration is chosen and then the stations relative to the first ones are coordinated by means of variometer measurements. Owing to the fact that the sensitiveness of absolute instruments is of the same order (if not higher) as that of the present variometers, the coordination can be made without difficulty.

Of course, care must be taken as to the manner in which the coordination is carried out, as this coordination can be done in many ways; the simplest method giving the highest possible accuracy must be selected.

In using the magnetometer, the application of the method of least-square adjustment can not be recommended, as it requires the use of the calculus. It is better to depend on accurate instruments and good operators than to have the illusion of possessing faultless results based on abstract mathematical theories, because the latter are justifiable only if the measurements made in the field are correct; but in this case there is no necessity for these theories.

The surveyor must try to be a good operator in the field and an ardent calculator in the office. But he must take care not to use his mathematical knowledge beyond the reasonable and necessary limits.

3. Magnetic Profiles

Two kinds of profiles may be used, according to necessity:

(a) Closed profiles.
(b) Open profiles.

Linear profiles come into the second category.

(a) The case of a closed profile does not occur usually in the magnetic prospection; it may be carried out in the case of localizing the borders of a mineral deposit; the error of the closure is then distributed linearly along the whole profile. Often, if there is only one absolute station and the surveyor wants to adjust to it the relative stations, it is preferable to distribute the latter around it and to carry out a certain kind of closed profile.

(b) The most usual case is that of open profiles; particularly that of rectangular profiles. This is the most used representation of magnetic prospection. On the same sheet of paper divided into squares or on a board showing the distribution of stations the consecutive profiles can be represented in the same way as the geological cuts (method used by Swiss school); in this case the interpretation is the easiest; the anomalies, as well as the various values at each station, are located on the map automatically.

In tracing the magnetic profiles the rectilineal system of coordinates is used; on the abscissa are drawn the mutual distances of the stations of measurement and on the ordinate the values of the anomalies measured, both of them at a convenient scale. It is recommended not to choose exorbitant scales. If there is no anomaly the anomaly which the surveyor may want to see will not appear by increasing the scale of the graphs. The scale to be chosen depends necessarily on the order of magnitude of the anomalies; thus its choice depends solely on the good sense of the operator.

4. Reconnaissance Profiles. Magnetic Charts

Before starting the execution of the network of the magnetic stations it is preferable to first make two magnetic profiles called the reconnaissance profiles. It is preferable to make them in the directions NE.-SW. and NW.-Se.; their intersection can be taken as a base station common to both of them. These reconnaissance profiles may have also the directions N.-S. and E.-W.; but according to the experience the first direction must be considered more suitable. If the time is limited or one reconnaissance profile seems to be sufficient, it is preferable to carry it out in the N.-S. direction for the sole reason that in general the geological formations are magnetically polarized in this direction and therefore there is maximum possibility to disclose the characteristic anomalies.

As soon as the existence of an anomaly is established it is necessary to cover the region with a network of stations, placed at regular distances. The most efficient method is the following:

The stations are distributed in a regular manner on two series of equidistant profiles intersecting one another at a right angle (preferably), so that the whole region to be explored is covered by a network of squares, the summits of which are occupied by the stations of measurement.

The mutual distances of the stations and the profiles must be between 50 and 150 meters, according to necessity; from the viewpoint of magnetic prospection distances of more than 150 meters must be considered too great.

In the course of exploration, measurement stations where the anomalies were found must be placed closer together than in other territory.

5. Representation of Numerical Operations

A constant system of calculations carried out by the assistant at the stations of measurement should be adopted. For the vertical component (the case when the Lloyd-Schmidt balances are used) the following system has been adopted:

N_w (Reading towards the West)		N_e (Reading towards the East)	
....		....	
....		....	
....		....	
....	(mean value)	....	(mean value

$$\frac{n + n}{2} = \ldots\ldots\ldots$$

Temperature (Beginning of the measurement.
(End of the measurement.

Hour (Beginning of the measurement.
(End of the measurement.

At the bottom of the sheet: Final calculations concerning the value of ΔZ.

This system can, of course, be varied by different operators. We recommend choosing the system which seems to be the most convenient. The chief point is to obtain a working notebook which may be easily deciphered.

6. Number of Stations Which can be Completed Per Day

The highest ambition of operators, especially if they are beginners, is to complete a great number of stations during one day.

But it must be kept in mind that 15 stations with reliable data are better than 40 with doubtful ones. It is recommended that not more than 6 magnetic stations should be completed in one hour; these 10 minutes per station (including the time necessary for traveling about 100 meters) are sufficient only for the best trained operators. As a general rule it can be considered that by working from 10 a.m. to 3 p.m., without interruptions, a maximum of 25 stations can be completed. Besides, toward the end of the day the fatigue and the enervation of the operator must also be taken into consideration, as these two factors may greatly reduce the accuracy of reading.